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AN ANALYTICAL COMPARISON OF THE EFFICIENCY OF SOLAR THERMAL COLLECTOR ARRAYS WITH AND WITHOUT EXTERNAL MANIFOLD

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For the U. S. Department of Energy

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Solar Energy

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LIST OF SYMBOLS

Symbol	Definition	Units
English:		
A^*	Collector efficiency parameter	—
A_g	Gross area of a single collector	ft^2
A_{gEM}	Gross area of a single collector including effective area of related external manifold	ft^2
A_p	Area of manifold tube (or pipe) between adjacent collector parts, πDL	ft^2
B^*	Collector efficiency parameter	$\frac{BTU}{ft^2.hr.^oF}$
$\bar{c}_p$	Mean value of flow media specific heat	$\frac{BTU}{lbm.^oF}$
D	Manifold tube (or pipe) outside diameter, not including insulation	ft
I_t	Total insolation in plane of collector	$\frac{BTU}{ft^2.hr}$
$K_{\alpha\tau}$	Incident angle modifier parameter obtained from ASHRAE 93-77 test method	—
L	Nominal length of manifold between adjacent collector inlet (or outlet) ports	ft
$\dot{m}$	Rate of flow of heat transfer fluid	lbm/hr
n	Number of collectors placed in parallel in collector array bank	—
Q	Heat loss (or gain)	BTU/hr
R	Overall effective thermal resistance of manifold insulation covering	$\frac{ft^2.hr.^oF}{BTU}$
t	Temperature	^oF

*A and B denote the first order collector efficiency parameters, respectively intercept and negative of slope, as determined from an ASHRAE 93-77 test.

LIST OF SYMBOLS (cont'd)

Symbol	Definition	Units
Greek:		
α	Solar absorptivity of collector absorber plate	
η_g	Efficiency of solar collector based on gross area (not including related area of external manifold)	
τ	Solar transmissivity of collector glazing	
Subscripts:**		
a	Referenced to ambient conditions	
B	Before mixing at an outlet manifold terminus	
C	Collector	
EM	External Manifold	
g	Referenced to gross area	
I	Inlet conditions	
j	Index (e.g., j=1 refers to first collector in array)	
L	Losses	
M	Manifold and mixed	
O	Outlet conditions	
U	Useful (e.g., Q_U is the useful energy output)	

**Example of subscripts: $t_{MI,j=1}$ denotes the manifold (M) inlet (I) temperature (t) for collector number one (j=1). $t_{MOM,j=2}$ denotes the manifold (M) outlet (O) temperature (t) for mixed (M) flow just downstream of the outlet of collector number two (j=2).

LIST OF FIGURES

1.0 PURPOSE

The purpose of this document is to present the results of an analytical determination of the effect of heat loss from solar thermal collector array manifolding on array thermal performance. The analysis computer program permits a direct comparison of array thermal performance with and without external manifolding.

2.0 SUMMARY

A simple FORTRAN computer program was written to permit the computation of the thermal performance of solar thermal collector arrays with and without external manifolds. Computations were carried out for arrays constructed from two example solar thermal collectors (Grumman Model 332A and General Electric Model TC100) that are to be used in the DOE Solar in Federal Buildings Program. The results of the analysis are presented graphically for typical external manifold sizes and thermal insulations and are compared directly with the collector alone thermal performance (i.e., the ASHRAE 93-77 thermal performance results based on collector alone gross area).

The results indicate significant degradation in collector array thermal performance for manifold insulation having thermal resistance $(R, \frac{hr.ft^2.^{o}F}{BTU})$ values of 2.0 or less. Values of R near 7.0 and greater denote little heat loss and performance degradation. Note that the determination of an effective collector area that includes any external manifolding and spacing between adjacent collectors is critical to adequate determination of array performance. The effect of the assumed effective area on array performance is shown graphically for the two cases computed along with the effect of the various insulation R values for the external manifold.

3.0 INTRODUCTION

Solar thermal collectors have been designed with a variety of inlet and outlet configurations. This is especially true in the case of flat plate and evacuated tube designs and has resulted in a variety of manifolding configurations, manifold pipe size, materials and insulations, varying quality of installation workmanship, etc.

Ideally, the system designer should minimize the amount of external manifolding required. The two most important reasons for this are as follows: 1) to reduce the physical space required for a collector array; and 2) to minimze manifold heat losses. It is obvious that the amount of useful energy collected per unit area will be diminished if the collector array wastes space unduly and if external manifolds are poorly insulated. Thus, collectors using internal (integral) manifolds are generally preferred when designing large arrays of such collectors.

Although there are many other advantages, as well as some disadvantages, to the use of collectors having internal manifold configurations, the intent of this report is to provide a general comparison of the area and heat loss related effects of externally versus internally manifolded collectors. Section 4.0 provides an overall discussion of the study, including the basic assumptions, analytical model, and computational parameters. Section 5.0 presents two example input data sets (two collectors) and Section 6.0 presents the results of the study. General conclusions from the study are presented in Section 7.0. A list of flat plate solar thermal collectors that may qualify as having internal (integral) manifolds is presented in Appendix A. Appendix B presents both a sample computer input and output and the program listing used in the present study.

4.0 DISCUSSION

4.1 Internal/External Manifolds-Definition. Except for those solar collectors that use a single serpentine flow path, most flat plate solar thermal collectors have a distinct internal header/riser configuration (Figure 1). The collector of Figure 1, as configured, requires a significant external manifold for it to be connected in parallel to another collector, or collectors, in an array bank. Thus, in this report the collector of Figure 1 will be treated as having an external manifold in spite of its header/riser configuration.

The collector examples shown in Figure 2 may be considered to fit the description of internally (integrally) manifolded collectors if designed as such. Obviously, such collectors will function adequately only if the headers and connectors must be adequately sized to maintain balanced flow rates in all of the risers.

4.2 Scope of the Present Study. The study described in this report provides a simple, accurate comparison of the instantaneous thermal efficiencies for real and idealized flat plate solar thermal collectors with and without internal (integral) manifolds. The following parameters were varied to evaluate their effect on collector array

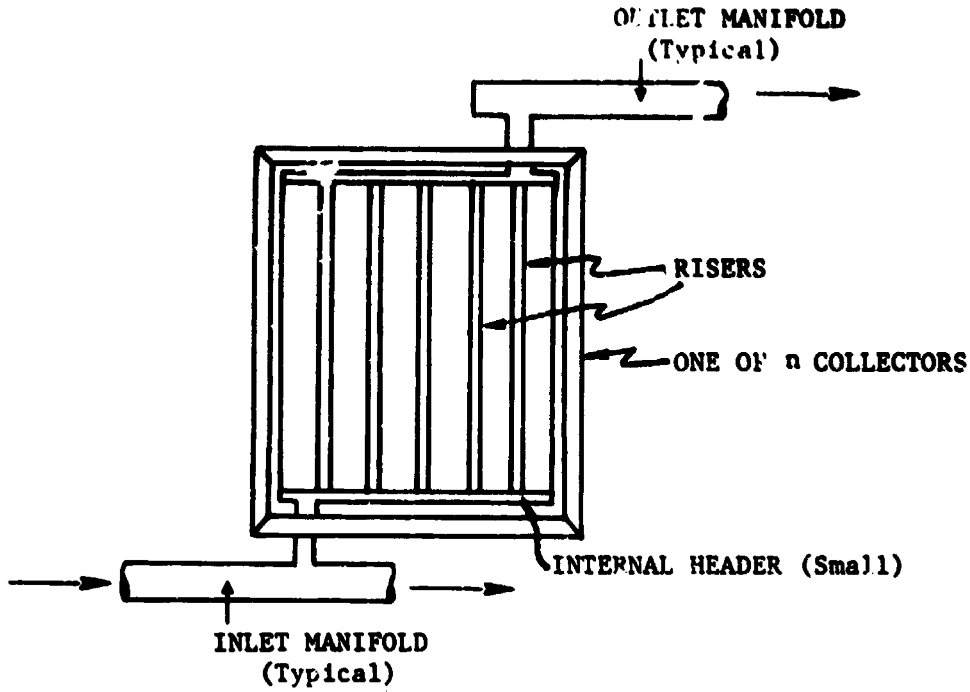

Figure 1. Typical Flat Plate Solar Thermal Collector With External Manifold Required

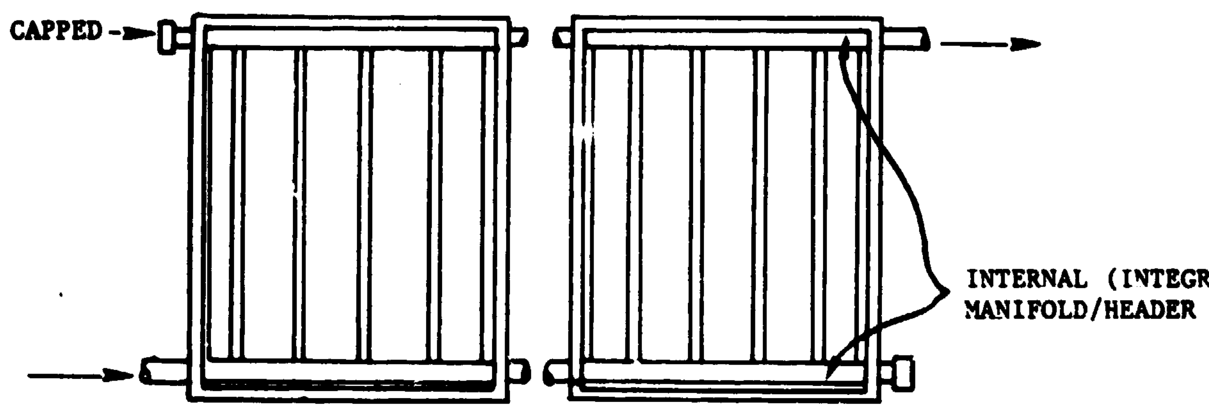

Figure 2. Flat Plate Solar Thermal Collector With Internal (Integral) Manifold/Header

efficiency:

1) Manifold Insulation Effective Thermal Resistance, $R = 0.75^*$, 2 and 7 $\frac{ft^2.hr.^oF}{BTU}$.

2) Number of Parallel Collectors in Array Bank, $n = 8$.

3) Average Ambient Temperature, $t_a = 40^oF$.

4) Manifold Inlet Temperature to Array Bank, $t_{MI} = 40.1\ ^oF$, $150\ ^oF$, and $220\ ^oF$.

4.3 Underlying Assymptions of Analysis. A set of assumptions was established to provide a simple, but realistically accurate analysis. It is deemed that no single assumption seriously limits the results of the current analysis:

1) All collectors in an array bank shall be identical and shall use a liquid as the flow media.

2) The liquid flow rate through each collector shall be identical and equal to $\dot{m}_c$.

3) External manifolds—when used—shall be of a constant diameter tube (or pipe) and be uniformly insulated.

4) Manifold heat losses (Q_{LM}) shall be determined from the input values of the effective insulation resistance (R) and the difference in the calculated mean fluid temperature, $\bar{t}_M$, between collector inlet (or outlet) ports and the ambient temperature, t_a, i.e.,

$$Q_{LM} = \frac{A_p}{R} (\bar{t}_M - t_a) \qquad (1)$$

and where A_p is the total tube (or pipe) area between collector ports on the same manifold.

5) The external manifolds receive no heat input from exposure to the sunlight.

* An R value of 0.75 $\frac{ft^2.hr.^oF}{BTU}$ approximates that of an uninsulated pipe.

6) The number of collectors, n, in an array bank shall be 10 or less for computation purposes.

7) The gross area of the collector array bank shall be defined as n times the effective gross area of a single collector. Two separate collector areas shall be input: a) A_g - the gross area of a single collector as defined by ASHRAE 93-77, and b) A_{gEM} - the effective gross area of a collector including its externally configured manifold. These two areas, A_g and A_{gEM}, are further defined in Figure 3.

4.4 Required Input Data. The following input data is required to perform the analysis for determining the effect of manifold heat losses and/or effective array size on collector array bank performance:

1) Collector efficiency parameters based on gross area (A_g) and first order curve fit in accordance with ASHRAE 93-77 test results (A, B, and $K_{\alpha\tau}$)

$$\eta_g = AK_{\alpha\tau} + B \quad (t_I - t_a)/I_t \qquad (2)$$

where B is defined in English units, $K_{\alpha\tau}$ is the incident angle modifier, t_I is the collector inlet (fluid) temperature, and t_a and I_t are defined below.

2) Ambient temperature, t_a (^{o}F)

3) Manifold inlet temperature, t_{MI} (^{o}F)

4) Total insolation measured in the plane of the collector, I_t $\left(\frac{\text{BTU}}{\text{hr.ft}^2}\right)$

5) Collector gross area, A_g (ft^2)

6) Collector effective gross area including external manifold, A_{gEM} (ft^2)

7) Flow rate through each collector, $\dot{m}_c$ (lbm/hr)

8) Mean value of flow media specific heat, $\bar{c}_p$ (BTU/lbm.^{o}F)

9) Number of collectors in array bank, n

10) Effective external area of manifold tube (pipe) between adjacent inlet (or outlet) ports, A_p (ft^2)

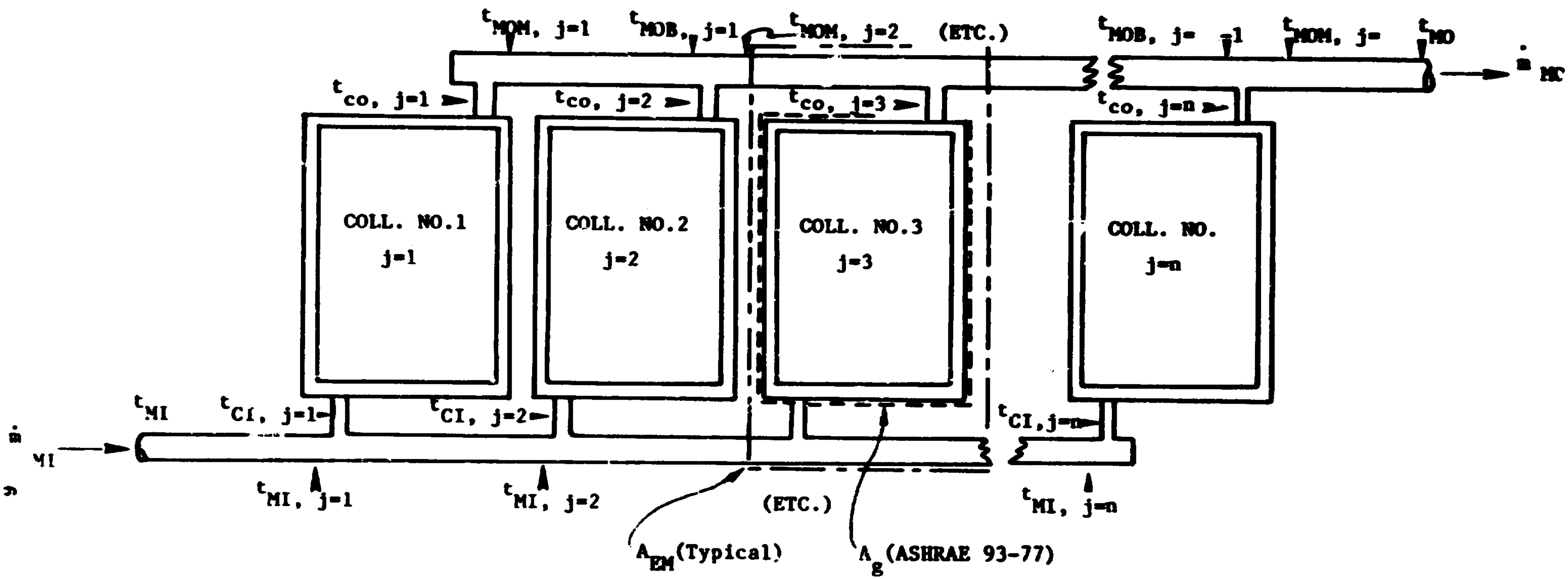

Figure 3. Typical Collector Array Bank With External Manifold

11) Effective thermal resistance of the manifold insulation, R ($hr.ft^2.^{o}F/BTU$). Note that the area, A_p, used in Equation (1) must correspond to the proper area as designated by the pipe insulation manufacturer. In this report the manifold pipe (tube) diameter is used in calculating the heat loss area.

4.5 Governing Equations. For simplicity in the current analysis, only linear equations and mean values of individual parameters have been utilized. Thus, the analysis proceeds with the following equations and in the general order presented.

4.5.1 Inlet Temperature for Inlet Manifold and Individual Collectors: Given the temperature, t_{MI}, of the flow at the start of the inlet manifold, the heat loss from each length of inlet manifold must be computed. With the assumption that the temperature change of the fluid in the manifold is linearly related to the manifold area, ambient temperature, and insulation thermal resistance, then the temperature at the terminus of a manifold length may be computed as follows:

$$t_{MI,j} = \frac{t_{MI,j-1}\left[(2\,\dot{m}_{MI,j})(\bar{c}_p) - (\frac{A_p}{R})\right] + \frac{2\,A_p t_a}{R}}{(2\,\dot{m}_{MI,j})(\bar{c}_p) + (\frac{A_p}{R})} \qquad (3)$$

Equation (3) is derived from an energy balance on a length of manifold, i.e.,

$$Q_{LMI,j} = \frac{A_p}{R}\ (\bar{t}_{MI,j} - t_a) \qquad (4)$$

and

$$Q_{LMI,j} = \dot{m}_{MI}\,\bar{c}_p\,(t_{MI,j-1} - t_{MI,j}) \qquad (5)$$

with the mean manifold fluid temperature defined as

$$\bar{t}_{MI,j} = (t_{MI,j-1} + t_{MI,j})/2.0 \qquad (6)$$

By defining $t_{MI,j-1} = t_{MI}$, the temperature at the terminus of each inlet manifold section may be determined by repeated application of Equation (3). Further, the inlet temperature of each collector, $t_{CI,j}$, is assumed to be equivalent to the terminus of each section of inlet manifold, i.e.,

$$t_{CI,j} = t_{MI,j}\ . \qquad (7)$$

4.5.2 Collector Efficiency and Collector Outlet Temperature. The outlet temperature of each collector must be determined to provide a boundary condition for the outlet manifold heat loss calculations. To accomplish this, the efficiency of each collector is computed from Equation (2) as follows:

$$\eta_{g,j} = AK_{\alpha\tau} + B\,(t_{CI,j} - t_a)/I_t. \tag{2}$$

Then, the collector outlet temperature is computed as follows:

$$t_{CO,j} = t_{CI,j} + \frac{\eta_{g,j}\, I_t A_g}{\dot{m}_c c_p}, \tag{8}$$

since

$$\eta_{g,j} = \frac{\dot{m}_c \bar{c}_p\,(t_{CO,j} - t_{CI,j})}{I_t\, A_g}\ . \tag{9}$$

4.5.3 Manifold Heat Losses: The equation for the manifold heat loss was introduced previously as

$$Q_{LM} = \frac{A_p}{R}\,(\bar{t}_M - t_a). \tag{1}$$

Equation (1) is written with the assumption that the mean value of the manifold flow media temperature, $\bar{t}_M$, may be computed by averaging the temperature at the beginning and terminus of the manifold section between adjacent collectors. With the appropriate subscripts, Q_{LM} may be formulated for both the inlet and outlet manifold sections.

Thus, for the array bank of Figure 3, the mean temperature of the flow media in the inlet manifold between collector no. 1 and collector no. 2 may be computed as

$$\bar{t}_{MI,j=2} = (t_{MI,j=1} + t_{MI,j=2})/2.0 = (t_{CI,j=1} + t_{CI,j=2})/2.0 \tag{10}$$

and so on for each inlet manifold length.

Similar computations may be made for determining the mean temperatures, $\bar{t}_{MO,j}$, in the outlet manifold with the exception that mixing must occur in the flow between the collector outlet ports and the corresponding outlet manifold location. Thus, the mixed flow media temperature downstream of the outlet port of collector no. 2 may be computed as follows

$$t_{MOM,j=2} = \frac{(t_{MOB,j=1})(\dot{m}_{MO,j=1}) + (t_{CO,j=2})(\dot{m}_c)}{\dot{m}_{MO,j=1} + \dot{m}_c} \tag{11}$$

and so on for each point at which mixing occurs. The temperature of the flow media at the terminus of each section of the outlet manifold may be computed through the application of Equation (3) with the appropriate assignment of subscripts, i.e.,

$$t_{MOB,j} = \frac{t_{MOM,j}\left[(2\dot{m}_{MO,j})(\bar{c}_p) - (\frac{A_p}{R})\right] + \frac{2A_p t_a}{R}}{(2\,\dot{m}_{MO,j})(\bar{c}_p) + \frac{A_p}{R}} \; . \tag{12}$$

4.5.4 <u>Collector Array Bank Efficiency</u>: After calculation of the temperature at the terminus of the outlet manifold, t_{MO}, the collector array bank efficiency and useful energy output may be computed from the following equations:

$$Q_U = n\dot{m}_c\,\bar{c}_p\,(t_{MO} - t_{MI}) \tag{13}$$

and

$$\eta_g = Q_U/(I_t\,A_g\,n)\,. \tag{14}$$

The choice of the gross area, A_g, to use in these computations depends on the effective area for each collector with consideration given to the added area due to the external manifold. Thus, the use of Equations 13 and 14 and the appropriate effective area permits a comparison to be made with the same array bank, when using only the gross area, A_g, of the collector alone.

5.0 EXAMPLE COMPUTATION

Two commercially available collectors were selected as examples for this analysis. The input data was generated from their individual ASHRAE 93-77 thermal performance results and from other assumed parameters listed below:

		Input Parameter Value for Each Collector	
Input Parameter	**Definition**	**Grumman**	**General Electric**
Model No.	Manufacturer's designation	332A	TC 100
A	Collector efficiency parameter	0.730	0.432
B	Collector efficiency parameter	0.844	0.078
$K_{\alpha\tau}$	Incident angle modifier	1.0	1.0
t_a	Ambient temperature	40^oF	40^oF
t_{MI}	Manifold inlet temperature	$(40.1, 150, 220)^oF$	$(40.1, 150, 220)^oF$
I_t	Total insolation	$310 \frac{BTU}{hr.ft^2}$	$310 \frac{BTU}{hr.ft^2}$
A_g	Gross area of a single collector	$31.80\ ft^2$	$17.41\ ft^2$
A_{gEM}	Gross area of a single collector including related external manifolds	$35.55\ ft^2$	$19.10\ ft^2$
$\dot{m}_c$	Collector fluid flow rate	400 lbm/hr	110 lbm/hr
$\bar{c}_p$	Mean specific heat of flow	$1.0 \frac{BTU}{lbm.^oF}$	$1 \frac{BTU}{lbm.^oF}$
n	Number of collectors in array bank	8	8
A_p	Area of manifold tube (pipe) between collector ports	$2.2\ ft^2$	$2.2\ ft^2$
R	Insulation thermal resistance of manifold covering	$(0.75, 2.0, 7.0) \frac{hr.ft^2.^oF}{BTU}$	$(0.75, 2.0, 7.0) \frac{hr.ft^2.^oF}{BTU}$

The effective gross area with external manifold (A_{gEM}) was estimated from the collector gross area (A_g) and the added area due to the manifold and collector spacing (Figure 3).

The temperatures and total insolation were chosen to produce a typical range of thermal performance for the example collectors. The insulation thermal resistance parameter (R) was varied from essentially no insulation $(R = 0.75 \frac{hr.ft^2.^oF}{BTU})$ to a relatively high degree of insulation $(R = 7.0 \frac{hr.ft^2.^oF}{BTU})$ for external manifolds.

6.0 RESULTS

The manifold heat loss analysis was applied to two separate collectors (Grumman Model 332A and General Electric Model TC100) as described in the example computation (Section 5.0). The results of the computations are shown in Figures 4 and 5 for the Grumman and General Electric collectors, respectively.

The curves labeled η_g in both Figures 4 and 5 represent the ASHRAE 93-77 thermal performance of the collectors based on the collector's gross area (A_g). The curves labeled η_{gEM} are representative of the ASHRAE 93-77 thermal performance modified by the effective gross area (A_{gEM}) of the collector including the external manifolds. Note that the value of the effective gross area must be carefully specified, since it is indicative of the gross "array" area used to produce useful collected energy.

Associated with each curve labeled η_{gEM} are thermal performance curves illustrating the effects of various pipe insulations. Values of the insulation thermal resistance (R) and the associated manifold area (A_p) between adjacent collectors are input to the computer program. Figures 4 and 5 show the effect on array efficiency with R values of 0.75 (essentially a bare pipe), 2.0, and 7.0 $\frac{ft^2.hr.^oF}{BTU}$. Thus, the computer analysis permits optimization of the pipe insulation type and its effective thermal resistance.

Note that the computer printout (see Appendix B) includes all of the inlet and outlet temperatures, manifold heat losses, and efficiencies of each individual collector. Also, the printout includes the array inlet and outlet temperatures, the useful energy delivered from the array and the array efficiency. Thus, manifold heat losses can be readily evaluated and plotted to indicate the energy lost by the array.

7.0 CONCLUSIONS

The computer analysis presented in this report permits an evaluation of the effect of various manifold insulations on solar thermal collector array efficiency. The analysis is simple and produces results quickly. It is believed that the assumptions made to develop the analysis aren't serious limitations to the method. The computer code can be easily modified. For example, the modification to the code to calculate the mean value of the flow media specific heat as a function of temperature may be readily accomplished.

The results indicate significant degradation in collector array thermal performance for manifold insulation having thermal resistance values of R = 2.0 hr.ft^2.$^\circ$F/BTU or less. Values of R near 7.0 and greater results in little heat loss and performance degradation.

Note that the determination of an effective collector area that includes any external manifolding and spacing between adjacent collectors is critical to adequate determination of array performance. The effect of the assumed effective gross area for the two example cases in this report show a dramatic effect on array efficiency.

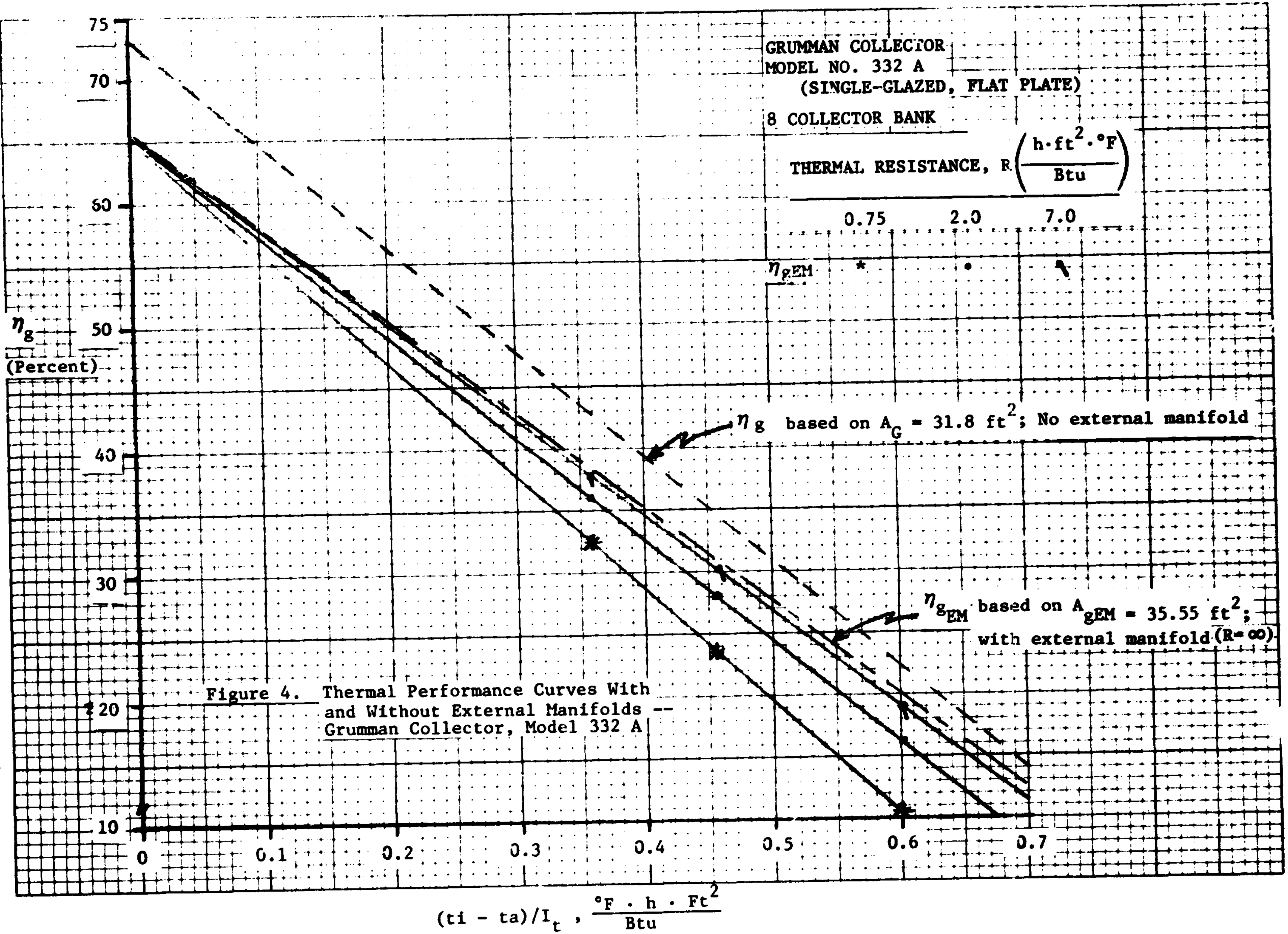

Figure 4. Thermal Performance Curves With and Without External Manifolds -- Grumman Collector, Model 332 A

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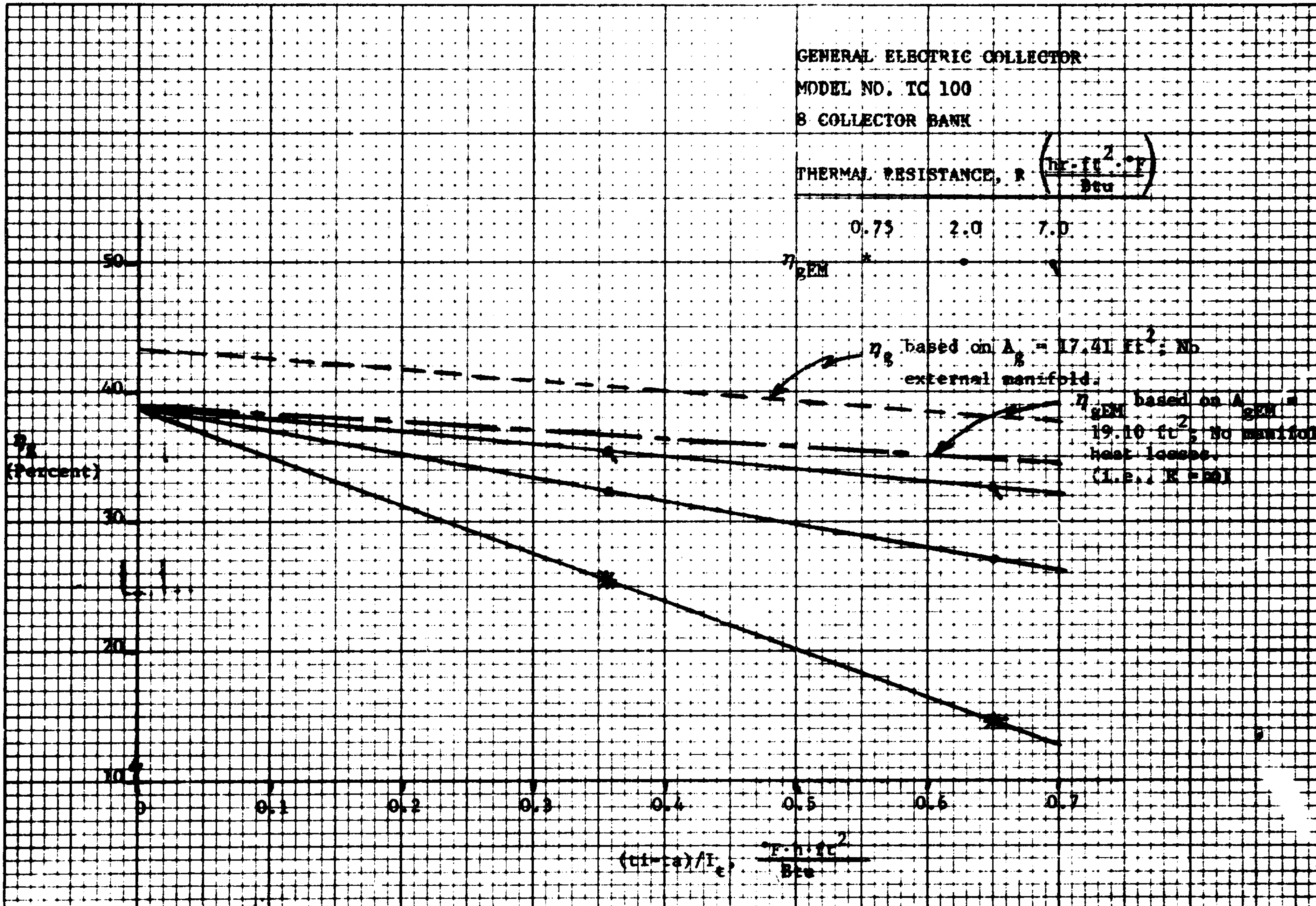

Figure 5. Thermal Performance Curves with and Without External Manifolds--General Electric Collector, Model TC 100

APPENDIX A

LIST OF COLLECTORS IN PHASE I OF THE DOE COLLECTOR TEST PROGRAM HAVING (INTERNAL) INTEGRAL MANIFOLDS

APPENDIX A (cont'd)

A cursory review of the collectors tested in Phase I of the DOE Collector Test Program indicate that the list of collectors below have (internal) integral manifolds. The list cannot be considered fully complete or accurate for the following reasons:

1) Approximately 20 sets of collector drawings and/or specifications were not available for review.

2) No evaluation was made of the flow capacity of the individual collector integral manifold, i.e., the number of collectors of a particular model that could be placed in parallel without an external manifold was not determined.

Approximately 100 sets of collector drawings were reviewed to identify the following 19 collectors believed to fall in the category of internal manifolds.

LIST OF COLLECTORS IN PHASE I OF THE DOE COLLECTOR TEST PROGRAM HAVING INTEGRAL (INTERNAL) MANIFOLDS

NAME	MODEL
Daystar Corporation	21-B, 21-C
Energy Systems, Inc.	1111D, 1111S
Federal Energy Corporation	F-200
Gulf Thermal Corporation	CU30-SL
International Technology/Solar Corporation	Mark III (4'), Mark V (3')
Oahu Solar Products	Solapak 150
PPG Industries, Inc.	C-524
Precision Industries, Inc.	50-11-3MG
Solar Energy Products, Inc.	CU-30-WW
Solar Enterprises, Inc.	SLIMLINER
Solar USA	28S, 37S
Solaron of North America, Inc.	SCO-200
Specialty Mfg. Co. (Insulator)	SA120-125SS
Sun Life Solar Products	SP-100
Sun Power Systems, Ltd.	C38B-H
Sunearth Solar Products Corporation	3597ADGFB
Sunworks Division of Enthorpe, Inc.	N/A
Wallace Company	Wallace Company Solar Collector
Wilcox Manufacturing Corporation	SC8000

APPENDIX B

SAMPLE PROGRAM INPUT/OUTPUT AND COMPUTER LISTING FOR COLLECTOR MANIFOLD STUDY

SAMPLE PROGRAM INPUT/OUTPUT

GRUMMAN COLLECTOR, MODEL 332A

```
COLLECTOR MANIFOLD STUDY
INTERCEPT EFFICIENCY=0.730    SLOPE=0.844
INCIDENT ANGLE MODIFIER VALUES FOR     0,10,20,...90 DEGREES ARE
 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
AMBIENT TEMPERATURE= 40.0   MANIFOLD INLET TEMPERATURE=220.0   TOTAL FLUX=300.0
COLLECTOR GROSS AREA=31.00    COLLECTOR GROSS AREA WITH E-M=35.55
COLLECTOR MASS FLOW RATE=400.00    FLUID SPECIFIC HEAT=1.000
NUMBER OF COLLECTORS= 8    MANIFOLD PIPE AREA(S)= 2.2    MANIFOLD R VALUE= 2

COLLECTOR NO. = 1   TCI=219.9   TCO=225.3   TMI=219.9   TMOM=225.3   TMOB=224.8
                    TBMI=220.0   TBMO=225.0   QLMI=198.0   QLMO=203.5
                    MDOTMI=3200.   MDOTMO= 400.   NG=0.224
COLLECTOR NO. = 2   TCI=219.9   TCO=225.2   TMI=219.5   TMOM=225.0   TMOB=224.7
                    TBMI=219.9   TBMO=224.9   QLMI=197.9   QLMO=203.3
                    MDOTMI=2800.   MDOTMO= 800.   NG=0.224
COLLECTOR NO. = 3   TCI=219.8   TCO=225.1   TMI=219.8   TMOM=224.9   TMOB=224.7
                    TBMI=219.8   TBMO=224.8   QLMI=197.8   QLMO=203.3
                    MDOTMI=2400.   MDOTMO=1200.   NG=0.224
COLLECTOR NO. = 4   TCI=219.7   TCO=225.0   TMI=219.7   TMOM=224.8   TMOB=224.7
                    TBMI=219.7   TBMO=224.7   QLMI=197.7   QLMO=203.2
                    MDOTMI=2000.   MDOTMO=1600.   NG=0.224
COLLECTOR NO. = 5   TCI=219.6   TCO=224.9   TMI=219.6   TMOM=224.7   TMOB=224.6
                    TBMI=219.6   TBMO=224.7   QLMI=197.6   QLMO=203.1
                    MDOTMI=1600.   MDOTMO=2000.   NG=0.225
COLLECTOR NO. = 6   TCI=219.4   TCO=224.8   TMI=219.4   TMOM=224.6   TMOB=224.6
                    TBMI=219.5   TBMO=224.6   QLMI=197.4   QLMO=203.1
                    MDOTMI=1200.   MDOTMO=2400.   NG=0.225
COLLECTOR NO. = 7   TCI=219.2   TCO=224.5   TMI=219.2   TMOM=224.5   TMOB=224.5
                    TBMI=219.3   TBMO=224.5   QLMI=197.2   QLMO=203.0
                    MDOTMI= 800.   MDOTMO=2800.   NG=0.226
COLLECTOR NO. = 8   TCI=218.7   TCO=224.1   TMI=218.7   TMOM=224.4   TMOB=224.4
                    TBMI=218.9   TBMO=224.4   QLMI=196.8   QLMO=202.8
                    MDOTMI= 400.   MDOTMO=3200.   NG=0.227
COLLECTOR ARRAY PERFORMANCE
                    TMII= 220.00   TMO  = 224.36
                    QUEM= 13965.   NEMAG=0.183   NEMAM=0.164
```

APPENDIX B (cont'd)

COMPUTER LISTING FOR COLLECTOR MANIFOLD STUDY

```
      DIMENSION TCI(10),TMI(10),QLMI(10),TBMI(10)
      DIMENSION TCO(10),TMOM(10),TBMO(10),QLMO(10),TMOB(10)
      REAL MDOTMI(10),KAT(10),IT,MDOTC,NG(10),
     C MDOTMO(10),NEMAG,NEMAM
1     CONTINUE
      WRITE(7,1001)
1001  FORMAT(' TYPE IN THE NUMBER OF COLLECTORS:'$)
      READ(5,*)NC
      IF(NC.LE.0) GO TO 600
      WRITE(7,1002)
1002  FORMAT(' TYPE IN THE INTERCEPT AND SLOPE (POS):'$)
      READ(5,*)A,B
      WRITE(7,1003)
1003  FORMAT(' TYPE IN THE E-W INCIDENT ANGLE MODIFIER'$)
      WRITE(7,1004)
1004  FORMAT(' FOR 0,10,20....90 DEGREES:'$)
      READ (5,*)KAT
      WRITE(7,1005)
1005  FORMAT(' TYPE IN THE AMBIENT TEMPERATURES:'$)
      READ(5,*)TA
      WRITE(7,1006)
1006  FORMAT(' TYPE IN THE TEMPERATURE AT THE '$)
      WRITE(7,1007)
1007  FORMAT(' MANIFOLD INLET:'$)
      READ(5,*)TMII
      WRITE(7,1008)
1008  FORMAT(' TYPE IN THE INSOLATION VALUE:'$)
      READ(5,*)IT
      WRITE(7,1009)
1009  FORMAT(' TYPE IN THE COLLECTOR GROSS AREA:'$)
      READ(5,*)AG
      WRITE(7,1010)
1010  FORMAT(' TYPE IN THE GROSS AREA WITH EXTERNAL MANIFOLD:'$)
      READ(5,*)AGEM
      WRITE(7,1011)
1011  FORMAT(' TYPE IN THE COLLECTOR FLOW RATE:'$)
      READ(5,*)MDOTC
      WRITE(7,1012)
1012  FORMAT(' TYPE IN THE SPECIFIC HEAT:'$)
      READ(5,*)CP
      WRITE(7,1013)
1013  FORMAT(' TYPE IN THE AREA OF THE MANIFOLD PIPE, PIDL:'$)
      READ(5,*)AP
      WRITE(7,1014)
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1014  FORMAT(' TYPE IN THE MANIFOLD R VALUE:'$)
      READ(5,*)R
      WRITE(6,2001)
2001  FORMAT(1X,'COLLECTOR MANIFOLD STUDY')
      WRITE(6,2002)A,B
2002  FORMAT(1X,'INTERCEPT EFFICIENCY=',F5.3,5X,
     C'SLOPE=',F5.3)




      WRITE(6,2003)KAT
2003  FORMAT(1X,'INCIDENT ANGLE MODIFIER VALUES FOR
     C 0,10,20...90 DEGREES ARE',/1X,10F7.3)
      WRITE(6,2004)TA,TMII,IT
2004  FORMAT(1X,'AMBIENT TEMPERATURE=',F5.1,3X,
     C 'MANIFOLD INLET TEMPERATURE=',F5.1,3X
     C 'TOTAL FLUX=',F5.1)
      WRITE(6,2005)AG,AGEM
2005  FORMAT(1X,'COLLECTOR GROSS AREA=',F5.2,5X,
     C 'COLLECTOR GROSS AREA WITH E-M=',F5.2)
      WRITE(6,2006)MDOTC,CP
2006  FORMAT(1X,'COLLECTOR MASS FLOW RATE=',F6.2,5X,
     C 'FLUID SPECIFIC HEAT=',F5.3)
      WRITE(6,2007)NC,AP,R
2007  FORMAT(1X,'NUMBER OF COLLECTORS=',I2,5X,
     C 'MANIFOLD PIPE AREA(S)=',F5.1,5X,
     C 'MANIFOLD R VALUE=',F5.2)
C     INITIAL CONDITIONS
      MDOTMI(1)=NC*MDOTC
      TCI(1)=(TMII*(2.*MDOTMI(1)*CP-AP/R)
     C +(2.*AP*TA)/R)/(2.*MDOTMI(1)*CP+AP/R)
      TMI(1)=TCI(1)
      TBMI(1)=(TMII+TCI(1))/2
      QLMI(1)=(AP/R)*(TBMI(1)-TA)
      DO 100 J=2,NC
      MDOTMI(J)=(NC-J+1)*MDOTC
      TCI(J)=(TMI(J-1)*(2.*MDOTMI(J)*CP-AP/R)
     C +(2.*AP*TA)/R)/(2.*MDOTMI(J)*CP+AP/R)
      TMI(J)=TCI(J)
      TBMI(J)=(TMI(J-1)+TCI(J))/2
      QLMI(J)=(AP/R)*(TBMI(J)-TA)
100   CONTINUE
      XKAT=1
      DO 200 J=1,NC
      NG(J)=A*XKAT-B*((TCI(J)-TA)/IT)
      TCO(J)=TCI(J)+(NG(J)*IT*AG)/(MDOTC*CP)
      MDOTMO(J)=J*MDOTC
```

```
200     CONTINUE
        TMOM(1)=TCO(1)
        TMOB(1)=(TMOM(1)*(2.*MDOTMO(1)*CP-AP/R)+
      C 2.*AP*TA/R)/(2.*MDOTMO(1)*CP+AP/R)
        DO 300 J=2,NC
        TMOM(J)=(TMOB(J-1)*MDOTMO(J-1)+TCO(J)*MDOTC)
      C /(MDOTMO(J-1)+MDOTC)
        TMOB(J)=(TMOM(J)*(2.*MDOTMO(J)*CP-AP/R)
      C +2.*AP*TA/R)/(2.*MDOTMO(J)*CP+AP/R)
300     CONTINUE
        DO 400 J=1,NC
        TBMO(J)=(TMOM(J)+TMOB(J))/2.
        QLMO(J)=(AP/R)*(TBMO(J)-TA)
400     CONTINUE




        TMO=TMOB(NC)
        QUEM=NC*MDOTC*CP*(TMO-TMII)
        NEMAG=QUEM/(IT*AG*NC)
        NEMAM=QUEM/(IT*AGEM*NC)
        DO 500 J=1,NC
        WRITE(6,3001)J,TCI(J),TCO(J),TMI(J),TMOM(J),TMOB(J)
3001    FORMAT(1X,'COLLECTOR NO.=',I2,3X,'TCI=',F5.1,
      C 3X,'TCO=',F5.1,3X,'TMI=',F5.1,3X,'TMOM=',F5.1,
      C 3X,'TMOB=',F5.1)
        WRITE(6,3002)TBMI(J),TBMO(J),QLMI(J),QLMO(J)
3002    FORMAT(23X,'TBMI=',F5.1,3X,'TBMO=',F5.1,3X,
      C 'QLMI=',F5.1,3X,'QLMO=',F5.1)
        WRITE(6,3003)MDOTMI(J),MDOTMO(J),NG(J)
3003    FORMAT(23X,'MDOTMI=',F5.0,3X,'MDOTMO=',F5.0,
      C 3X,'NG=',F5.3)
500     CONTINUE
        WRITE(6,3006)
3006    FORMAT(1X,'COLLECTOR ARRAY PERFORMANCE')
        WRITE(6,3005)TMII,TMO
3005    FORMAT(23X,'TMII=',F7.2,3X,'TMO  =',F7.2)
        WRITE(6,3004)QUEM,NEMAG,NEMAM
3004    FORMAT(23X,'QUEM=',F7.0,3X,'NEMAG=',
      C F5.3,3X,'NEMAM=',F5.3)
        GO TO 1
600     CONTINUE
        STOP
        END
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